# Unravelling strange quarks in nucleon structure

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**Abstract.** We present a discourse on the stages of discovery that have led to a deeper understanding of the role played by strange quarks in the structure of the nucleon.

## INTRODUCTION

The determination of the strange quark content of the nucleon offers a unique probe to measure the nonperturbative structure of the nucleon. As the nucleon carries zero net strangeness, the influence of strange quarks arises entirely through interaction with the vacuum. In essence, the strange quarks play a role analogous to the Lamb shift in QED. While strangeness contributions to nucleon structure have been difficult to isolate, the measurement of the neutral weak current in elastic scattering offers perhaps the most direct observation of the strange quark content of the nucleon [1]. Here we highlight advances in the theoretical determination of the strangeness electromagnetic form factors, and compare with experimental measurements. Further, we discuss recent work that has provided an accurate determination of the strangeness sigma term based on a chiral extrapolation of lattice QCD results.

## CHIRAL PHENOMENOLOGY OF DISCONNECTED QUARKS

In early lattice QCD simulations, extrapolations to the physical quark masses largely neglected the importance of incorporating the dynamical consequences of chiral symmetry breaking in QCD. Indeed it is evident that (at least) part of the rationale for neglecting these features was the empirical observation that lattice results displayed smooth and slowly-varying dependence on the quark mass — contrasting the rapid nonlinear effects that must exist provided QCD's chiral symmetry is spontaneously broken. A solution to explain the rather linear behaviour of the lattice results *and* incorporate the correct dynamical constraints of QCD was identified in early work, see Refs. [2, 3, 4] for instance. This work used a momentum-space cutoff (or finite-range regularisation) to supress the high-momentum interations between baryons and pions, such as to supress the interactions of pion-loop dressings once the pion Compton wavelength is small relative to the (axial) size of the baryon.

The success of this work was extended to baryon masses in quenched lattice simulations [5] — which acted as a further testing ground, given the more readily available

quenched results at the time. The chiral extrapolation of this work identified quenching artifacts to be much larger than previously claimed [6] — results that have since been confirmed by improved quenched simulations in the chiral regime [7, 8].

A surprising result of the work in Ref. [5] was the observation that the differences in quenched and dynamical baryon masses[1] could be largely described by finite-range regularised chiral loops. This discovery opened the possibility of estimating the effects of quenching, and thereby providing improved estimates of QCD observables from quenched simulations.

This description was extended to the proton magnetic moment [9], which enabled a determination of the proton magnetic moment from quenched lattice simulations. To this date, the *proton* magnetic moment has still not been calculated in dynamical simulations — as the disconnected contribution continues to be neglected.

With a description of the unquenching effects in baryon properties, which appears to work for masses and magnetic moments, one had the confidence to extend to more ambitious observables — such as the flavour separation of the nucleon electromagnetic form factors. In particular, the isolation of the strangeness component of these form factors.

In combination with charge-symmetry relations among the octet-baryon magnetic moments [10], our analysis enabled a precise determination of the strangeness magnetic moment, $G_M^s = -0.046 \pm 0.022 \, \mu_N$ [11, 12]. A strong indicator of the reliability of this analysis was the excellent agreement found with the experimentally determined baryon magnetic moments.

Further extensions within the same framework enabled the determinations of the strangeness charge radius [13] and the strangeness magnetic form factor at $Q^2 \sim 0.23 \, \text{GeV}^2$ [14]. These results, especially the magnetic moment, challenged the best experimental determinations at the time.

## STRANGENESS MEASUREMENTS

The strangeness contributions to the vector form factors of the nucleon can be probed in parity-violation measurements. Early combinations of different measurements suggested discrepancy with the described theory calculation [15, 16, 17], with $G_M^s$ indicated to be positive at roughly 2-sigma — constrasting the precise negative value shown above.

A comprehensive global analysis of the original experimental asymmetries [18] — including a consistent treatment of electromagnetic form factors and radiative corrections; a Taylor expansion of $G_E^s$ and $G_M^s$; and an experimental extraction of the anapole form factors — led to an extraction of strangeness found to be in much better agreement with the predictions outlined above. Shortly after, this analysis was further supported by the high-precision HAPPEX measurement [19] on both hydrogen and helium targets. A combined global analysis of the form factors at that point in time is shown in Figure 1.

Though yet to be incorporated in the global analysis, recent back-angle results at

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[1] The quenched and dynamical simulations are "matched" by choosing an intermediate-range (non-chiral) scale, such as $r_0$, to set the lattice spacing.
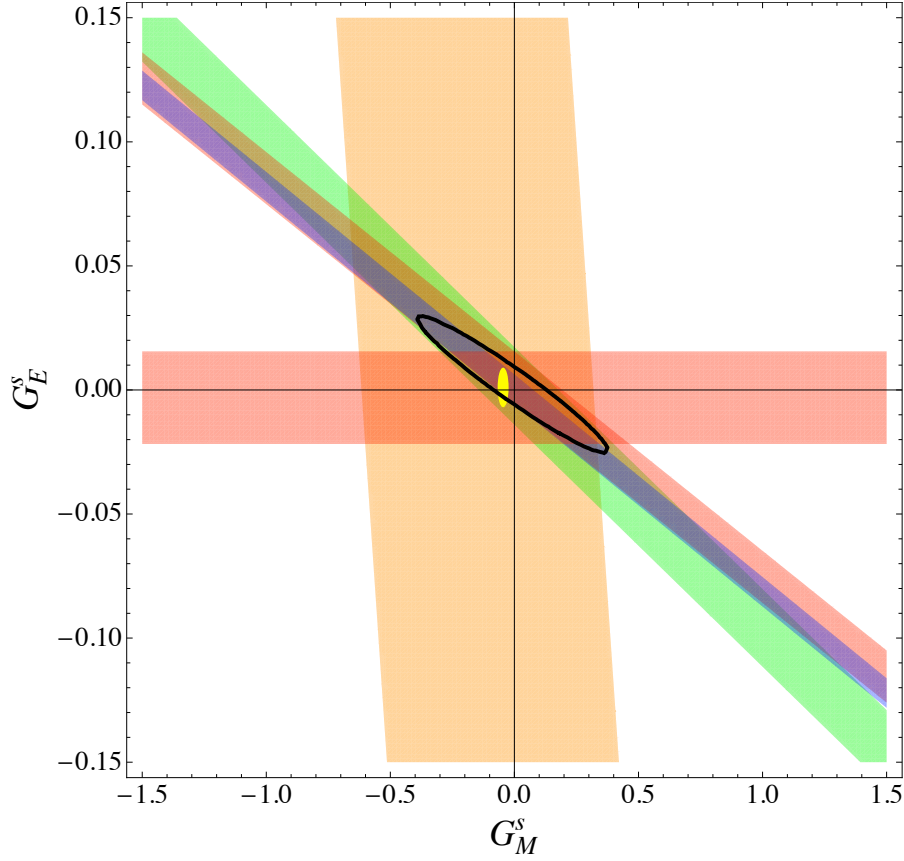
**FIGURE 1.** Summary of experimental determination of strangeness form factors at $Q^2 = 0.1 \, \text{GeV}^2$. Open ellipse depicts the combined 68% confidence interval of the experimental results. The filled ellipse displays the theory calculation described.

slightly higher $Q^2$ also support the findings of a small strangeness [20, 21]. A recent direct lattice QCD calculation of the strangeness form factors [22] also supports this scenario.

In addition to resolving the strange quarks in the nucleon, the collective precision of the parity-violation measurements provides a robust test of the electroweak interaction. The broad kinematic coverage of G0 [17] and precision of HAPPEX [19] provides a reliable extrapolation to extract the weak charge of the proton [23]. In combination with earlier atomic parity-violation measurements [24], the proton measurement places tight constraints on new electroweak physics up to a characteristic energy scale of $\sim 1 \, \text{TeV}$.

## STRANGENESS SIGMA TERM

While the unquenching component of the theoretical strangeness analysis relied on the phenomenological description of sea quark effects, the strength of the extrapolation to the physical point relied heavily on the methods of finite-range regularization detailed in Refs. [3, 25, 26]. Here it was established that there is very minimal dependence on
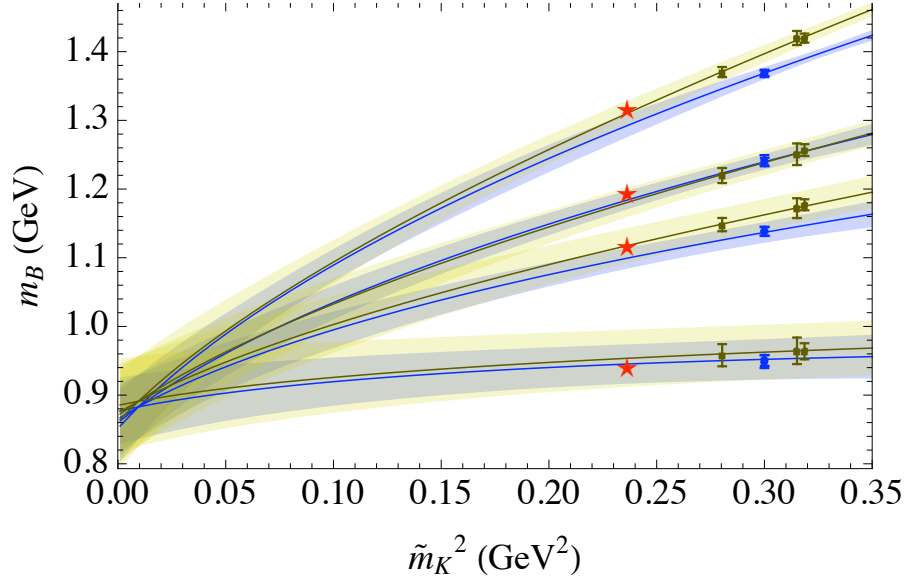
**FIGURE 2.** Extrapolation in the strange quark mass, holding the light quarks *fixed* at the physical point. The square data points and matching contours display the PACS-CS as extrapolated to the physical pion mass, while the circles are those of the LHPC extrapolation. From bottom–top displays the $N$, $\Lambda$, $\Sigma$ and $\Xi$ baryon, with the physical masses indicated by the stars.

the choice of regulator. With the latest generation of lattice simulations now taking full account of the 3 light flavours of dynamical quarks, the methods of FRR can now be utilised without the need to incorporate the model-dependent unquenching component.

Recent lattice QCD results for the octet baryon masses, using 2+1-flavours of dynamical quarks [27, 28], have been extrapolated using an SU(3) chiral extrapolation with FRR [29]. The results of this analysis produce precise values for both the absolute baryon masses and the associated sigma terms.

The full functional form of the fits permits a comprehensive description of the baryon masses over a range of quark masses. In Figure 2 we show the dependence on the strange quark mass, as it is taken from the lattice results and down through the physical point to the strangeness chiral limit. This figure is plotted against the SU(2) chiral limit kaon mass, $\tilde{m}_K^2 = m_K^2 - \frac{1}{2}m_\pi^2$, which we use as an effective measure of the deviation of the strange quark mass from the chiral limit. The figure is shown for the pion mass being held fixed at the physical point. The lattice results are individually extrapolated to the physical pion mass using the respective (LHPC or PACS-CS) fit result. The figure indicates the effective spread in the strange-quark mass probed by PACS-CS (the two LHPC points considered are at essentially the same strange-quark mass). The error bars on the points just show the original lattice error bar (including finite-volume uncertainty), whereas the shaded region depicts the full uncertainty at these points including the extrapolation to the physical pion mass.

An important feature of this figure is the very weak dependence of the nucleon mass on the strange quark. This leads to a particularly small value for the strangeness sigma term, $\sigma_{Ns} = 31 \pm 15\,\mathrm{MeV}$ [29]. This value is compatible with an independent direct lattice extraction by Toussaint and Freeman, $\sigma_{Ns} = 59 \pm 10\,\mathrm{MeV}$ [30].

We note that this consensus on a small strangeness sigma term is also being supported by a 2-flavour lattice analysis of Ohki *et al.* [31], and preliminary results of their extensions to the 3-flavour case [32]. Further, a recent chiral analysis of the PACS-CS results above, using an alternative regularization scheme, finds a compatible set of sigma terms for the octet baryon ensemble [33] to our determination report in Ref. [29].

One consequence of this improved precision in the determination of the strange quark sigma term is a dramatic reduction in the uncertainties of dark matter cross sections in a range of supersymmetric models [34]. The predicted cross sections are found to be substantially smaller than previously suggested. While this is somewhat unfortunate from an experimental perspective, the new level of precision does indicate that any observation of dark matter would have substantial discrimination power amongst the class of benchmark models that have been considered.

## CLOSING REMARKS

It is evident that the strange quark contributions to the structure of the nucleon are smaller than early estimates had suggested. Indeed, at the 2-sigma level, the strangeness magnetic moment and mean-square charge radius of the proton are less than about 6% of their total values. Conservatively, the strangeness sigma term appears to lie somewhere in the range of just 2–7% of the nucleon mass.

We look forward to the next decade of discoveries that will continue to improve our understanding of the nonperturbative nucleon.

## ACKNOWLEDGEMENTS

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